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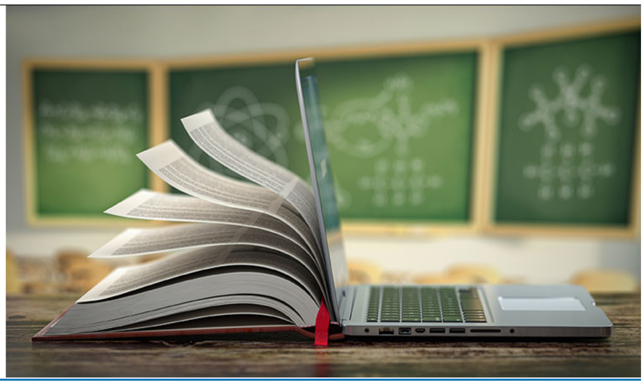

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Development of an integral criterion for evaluating the degree of aging of transformer oils

I Davidenko, A Egorov

Department of electrical machines Ural Federal University named after the first President of Russia B. N. Yeltsin.
Ekaterinburg, Russia

i.v.davidenko@urfu.ru

Abstract. The technical condition of the transformer oil affects the condition of the solid insulation, and therefore the residual life of electrical equipment, so it is important to study the aging mechanisms of the oil. The mechanism of transformer oil aging is studied using factor analysis of oil quality indicators, such as moisture content, acid number and dissipation factor tangent. Factors that have the greatest influence on the rate of oil aging have been found. In accordance with the found influence factors the permissible values of oil quality parameters of 110 kV power transformers with division by equipment tightness, oil brands and operating time have been determined. Oil aging models, taking into account the mutual influence of oil quality parameters, have been developed for transformers with different oil brands, type of oil protection and service life. An integral index, characterizing different aging processes of the oil, has been proposed. The criterion for evaluating the integral index of oil aging rates is calculated.

1. Relevance

The task of precise evaluation of technical condition of power system assets and management of this condition is always relevant. As the proportion of equipment with a long service life increases, the importance of this task only grows.

It is known that the reliability of oil-filled electrical equipment is primarily determined by the condition of its solid insulation, which is in constant interaction with the transformer oil. The quality of transformer oil affects the state of its solid insulation [1,2,3], so it is important to study the mechanisms of oil aging.

The sets of parameters characterizing the quality of transformer oil in national standards vary [4,5,6]. However, the moisture content of the oil (H_2O, g/t), the acid number (KOH, mgKOH/g) and the dielectric loss tangent (Tg 90°C, %) are included in international and national standards. These oil quality parameters describe the main processes that characterize the ageing of an oil: moisturizing, oxidizing the oil as well as the formation of colloidal compounds in it.

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In our opinion, the existing approach to assessing these indicators has two drawbacks. First, the system regulating these indicators is not differentiated by the factors affecting the values of the parameters. The works [7,8,9] show that such factors are tightness of the equipment, oil grade, voltage class [7,8], load and temperature mode of the equipment, as well as its service life [7,9].

Secondly, in existing international and national standards [4,5,6] regulating values of oil quality parameters, parameters are considered independently from each other. Meanwhile, the authors [10,11] noted a significant correlation between these parameters.

2. Purpose of work

The aim of the work is to study the force of mutual influence of power transformers' (PT) oil quality parameters, as well as to develop an integral index, describing the influence of several processes, characterizing the oil aging at once.

This study is based on observation of real changes in the technical condition of 110 kV transformer oil during its operation.

3. PT operation data

The results of physicochemical analysis of the oil, accumulated in the database of the Expert Diagnostic Information System (EDIS "Albatross") for 30 years of its operation at power grid enterprises of the Russian Federation, were used as the initial data.

The initial sample for 110kV class voltage transformers was 32565 results of physicochemical oil analysis. In our previous studies [7,8,11] it was found that the quality characteristics of the oil (its aging rate) are influenced by tightness, voltage class, service life of oil-filled equipment and the content of aromatic hydrocarbons (Ca) in the oil. Therefore, the initial sample was divided according to the type of oil protection (free breathing and membrane protection) and oil brands. Ten oil brands are used in the Russian power transformer fleet, which were divided into three groups depending on the aromatic hydrocarbon content:

- with a minimum content Ca *min* $\leq$ 3%;
- with an average content 3 < Ca *mid* $\leq$ 15%;
- with a maximum content Ca *max* $\geq$ 18%.

The fourth group was transformers with a long service life, in which a mixture of different oil brands was formed by refilling oils different from the original oil (Oil mix).

4. Preparing data for analysis

First, the subsamples of the measurement results of the oil moisture content (H_2O, g / t), acid number (KOH, mgKOH / g) and dielectric loss tangent (Tg 90 °C, %) were cleared of errors in data entry by personnel.

Then, we needed to normalize the parameters so that they are presented equally in the factor analysis.

For normalization, permissible values (PV) of parameters were determined for each subsample by the integral distribution function at the level of 0.95.

Table 1 shows the calculated values for the most representative sample of PT 110 kV with free breathing and a group of oil brands with average aromatic hydrocarbon content of Ca *mid*.

Table 1. Permissible oil quality values of Ca *mid* group for power transformers 110 kV with free breathing

Parameter	H_2O (g / t)	KOH (mgKOH /g)	Tg 90 °C (%)
PV of parameter	28	0.06	4.9

Previous studies [7,8,9] have shown an increase in the values of these parameters as the lifetime of the transformer increases. To study the mutual influence of the parameters, we used for their normalization PV without differentiating them according to the operating life, so as not to introduce distortions into the original data array.

Further, the analyses in which the value of at least one of the three parameters was absent were removed from the investigated subsamples.

Oil breakdown voltage was excluded from the analysis of mutual influence of parameters, as this parameter is an indicator of oil moisture and contamination. As a rule, the breakdown voltage duplicates the oil moisture content of the oil, since oil contamination in modern power transformers is higher than the permissible values, this phenomenon is extremely rare.

5. Analysis of mutual influence of oil quality parameters

The correlation analysis given in the articles [10, 11] showed mutual influence of the investigated oil quality parameters (H_2O, KOH, Tg90 °C).

The task of the study is to find an integral indicator of oil aging, linking the values of three studied parameters (H_2O, KOH, Tg90 °C). The factor analysis is suitable for this purpose as it is a multivariate statistical analysis that combines methods for estimating observed variables by studying the structure of covariance or correlation matrices.

Recall that the initial sample of parameter measurements (H2O, KOH, Tg90 ° C) divided by the type of oil protection and oil brands.

Then, for each of the obtained subsamples, a factor analysis was performed with a breakdown by service life into subgroups of 6 years.

As a result of the analysis, the following equations were obtained:

$$I = k_1 \cdot x + k_2 \cdot y + k_3 \cdot z \tag{1}$$

where k_1, k_2, k_3 are the force coefficients of the parameters' influence on the oil aging rate;
x, y, z - normalized values of investigated parameters (H_2O, KOH, Tg90°C).

The graphs shown in Figure 1 have been used to analyze changes in the coefficients of parameters' influence on the oil aging rate depending on the operating time of transformers and the aromatic hydrocarbons content in their oil.

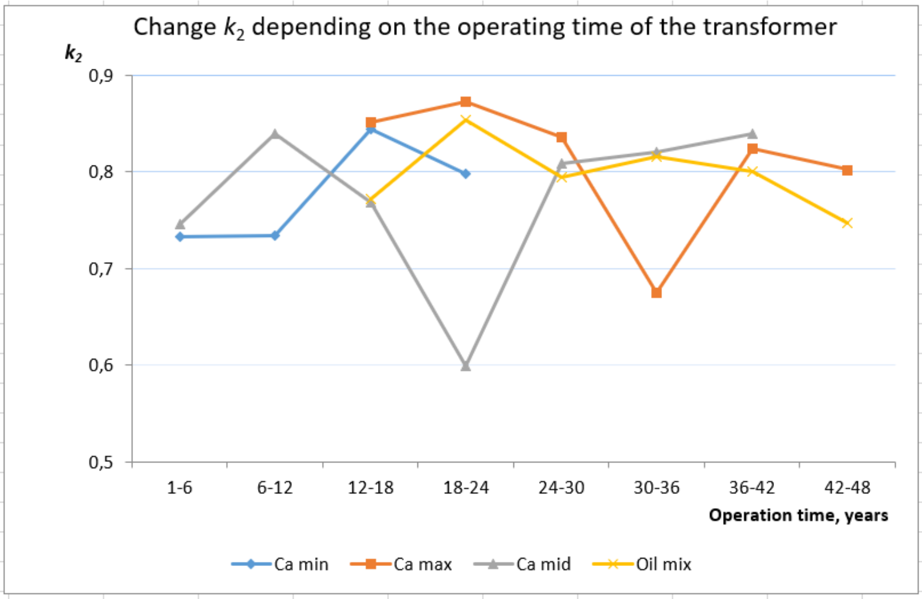

Figure 1. Change of force of influence of KOH value on oil aging rate depending on transformer operation time and aromatic hydrocarbons content in oil.

A minimal variation in the values was observed for the coefficient k2 of the acid number: 0.6-0.88. The maximum variation in the values was for the coefficient k1 of moisture content of the oil: 0.32-0.82. The variation in the values of the coefficient k3 of the tangent of the angle of dielectric loss of oil was: 0.56-0.86.

Based on the analysis of the variability k1, k2, k3 depending on the operating time PT, the following conclusions were made. With age, the strength of the mutual influence of oil aging products increases. After the operational measures (drying of the oil, change of silica gel in the thermosiphon and air-drying filters, oil regeneration, addition of antioxidant additives to the oil), the aging process slows down. During this period, the synergy of the processes of oxidation, moistening of the oil, and the formation of colloidal forms in it weakens. Then, the aging rate of the oil increases until the next operational measures. The second period of oil deterioration is shorter than the first.

Analysis of the variability k_1, k_2, k_3 depending on the content of aromatic hydrocarbons in the oil showed that the oils of the Ca *min* group are more slowly oxidized but moisturized faster than the oils of the Ca *mid*, Ca *max* groups. In addition, with longer service lives, more colloidal forms are formed in them than in Ca *mid*, Ca *max* oils. Mixtures of different brands of oils have the highest rates of moisture and oxidation, as well as the formation of colloidal forms.

6. Criteria for evaluating oil quality by integral criterion

The task of the next stage of the study was to obtain the value of integral criterion for oil quality assessment.

Recall that at the previous stage of the study for each of the data sub-samples were determined values of force coefficients of the influence of parameters on the aging rate of oil (k_1, k_2, k_3).

For example, for a 110 kV power transformer with free breathing with oil brands Ca *mid* with an operating life of 12 to 18 years, the integral value was calculated using a formula:

$$I = 0.58 \cdot x + 0.8 \cdot y + 0.73 \cdot z \tag{2}$$

x, y, z - normalized values of investigated parameters (H_2O, KOH, Tg90°C) in operation.

After calculating all the values of the integral index of the subsample I, its permissible value I_{pv} was calculated from the integral distribution function at the level of 0.95.

The value of I_{pv} = 2.2 is a criterion that separates cases of accelerated deterioration in the quality of the oil from its normal aging in operation.

The following figures show graphs of oil quality parameters of two transformers operating in the same substation with the same load and operating time. And the value of integral index at transformer T1 is greater than that of transformer T2. As we can see, the trends of deterioration of oil quality parameters (H_2O, KOH, Tg90°C) of transformer T1 are higher than those of transformer T2.

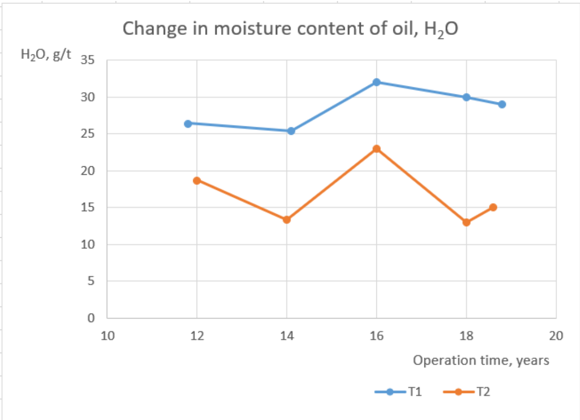

Figure 2. Change in moisture content of oil, H_2O.

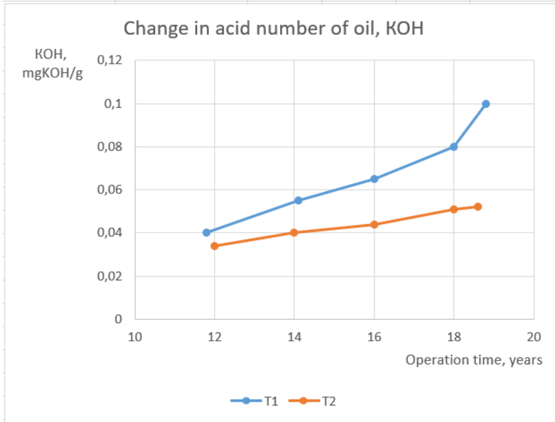

Figure 3. Change in acid number of oil, KOH.

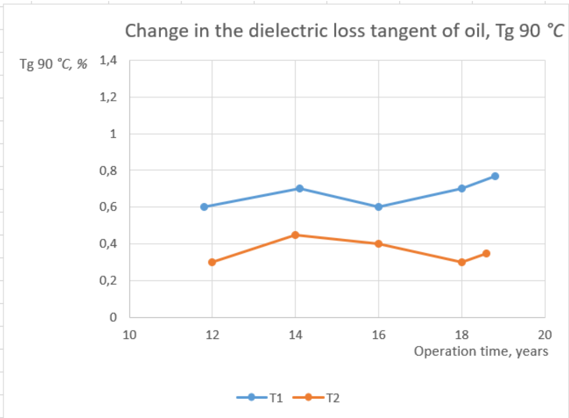

Figure 4. Change in the dielectric loss tangent of oil, Tg 90 °C.

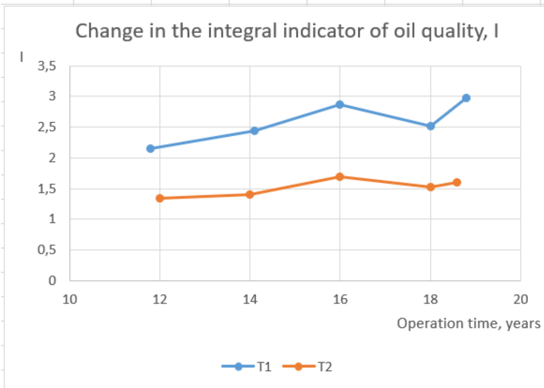

Figure 5. Change in the integral indicator of oil quality, I.

Accordingly, the assessment of oil quality by an integrated indicator allows us to identify transformers with high rates of oil aging and put them in a timely manner on frequent control. Evaluation of the parameters H_2O, KOH, Tg90 ° C individually can lead to the fact that the transformer with rapidly degrading oil will be monitored at regular intervals (1 time in 2 years).

Detection of deep oil degradation will only be possible after 2 years, when it will already have a devastating effect on the solid insulation of the transformer.

7. Conclusion

The research confirmed the necessity of differentiation of oil quality assessment criteria (H_2O, KOH, Tg90°C) by equipment tightness, aromatic hydrocarbons content in oil, operating time. Permissible values for assessment of parameters H_2O, KOH, Tg90°C with necessary differentiation have been determined.

Oil aging models including H_2O, KOH, Tg90°C parameters and their mutual influence were found for transformers with different oil grades, type of oil protection and operating life.

An integral index characterizing the oil aging processes such as moistening, oxidation, colloidal formation is proposed. The criterion for evaluating the integral index of oil aging rates has been calculated.

The obtained dependencies (formula 1) describing the oil aging process as well as the criterion of integral index evaluation can be used with the help of predictive analytics for medium-term planning of oil regeneration (replacement), determination of optimal frequency of oil quality control.

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